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Modeling and Simulating of Renewable Energy Resources

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Abstract

To understand the detail properties of the renewable energy resources such as solar PV, wind power and small hydro needs to be modeled and simulated technically. So that each of the three renewable energy resources will be mathematically modeled and simulated using MATLAB Simulink. Hence then, it will be easy to design and use their output in a small effort and minimal cost. After all, it will be easy to control the intermittency nature of these resource considering their detail properties.

Keywords: Intermittent, MATLAB, Simulink, Small Hydro, Solar PV, Wind Power

1. Introduction

Nowadays, renewable energy generations such as solar, wind power and small hydro acting as distributed generations (DGs) are attracting more and more considerations [1]. The main problem of these renewable energy resources is the intermittency nature these resources. Those energy resources are not continuously generate energy due to different reasons and by nature. For instance the sun shines only on daylight hence there will not be energy produced by sun between the sunset and sunrise. Furthermore even at the daylight the sun may not fully shine due to some weather conditions such as clouds. Similarly on all the other renewable resources they have their own reasons as they have intermittency nature in producing the necessary energy to satisfy the demand at hand. To reduce the intermittency nature of those energy sources initially it needs to carefully study and modeling of each resource. After carefully studding the detail properties it will be easy to put a solution for the intermittent (to minimize) problem. Here under a detail way of modeling and simulation for each energy resource is presented.

2. Modeling the Renewable Energy Resources

Modeling and Simulating of the Individual RERs: The renewable energy resources (RERs) selected for this paper are the wind power, solar power (PV) and small hydropower. Hence all these three RERs will be modeled and simulated individually. Hence here is the modeling and simulating for each RERs. Simulations using MATLAB software are performed to highlight the characteristics of the output voltage, current and power when the inputs (such as irradiation, wind speed and water flow) are varying.

2.1 Solar Energy Modeling and Simulations [2][3]

Solar energy is the sun’s rays (solar radiation) that reach the earth. It is one of the naturally gifted resource of energy. It is available in most parts of the world though the rate of availability has a lot of differences. The major disadvantages of solar energy are the amount of sunlight that arrives at the earth's surface is not constant. It depends on location, time of day, time of year, and weather conditions. Because the sun doesn't deliver that much energy to any one place at any one time, a large surface area is required to collect the energy at a useful rate.

Cause of Intermittency: Amount of solar radiation, Seasonal variations, Weather conditions, Sun’s energy concentration, Temperature.

Photovoltaic (PV devices) or Solar Cells: It change sunlight directly into electricity. PV systems are often used in remote locations that are not connected to the electric grid. They are also used to power watches, calculators, and lighted road signs.

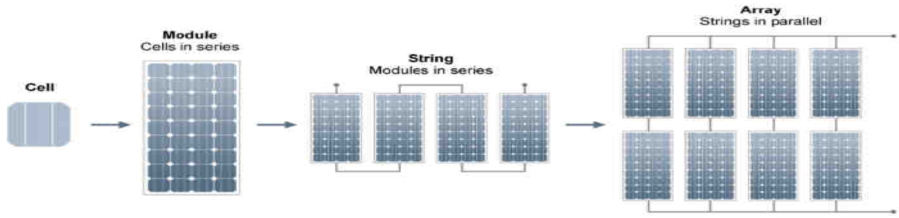

Figure 1: Parts of the solar PV panel and some possible arrangements

Mathematical Equivalent Circuit for Photovoltaic Array

Practically, PV cells are grouped in larger units called PV modules and these modules are connected in series or parallel to create PV arrays which are used to generate electricity in PV generation systems. One-diode equivalent circuit is employed in order to investigate I-V and P-V characteristics of a typical 213.15W solar module. The equivalent circuit for PV array is shown in figure 2 below.

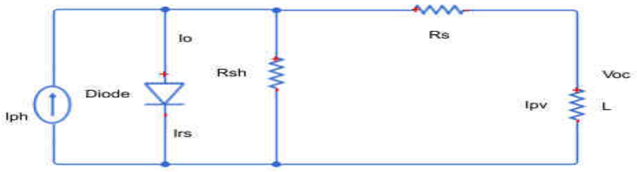

Figure 2: PV cell equivalent circuit modeled as diode circuit

I_{ph}= the current source which represents the cell photocurrent (light-generated current)
R_{sh} = the intrinsic shunt resistances of the cell, $R_{s=}$ the intrinsic series resistances of the cell
Most of the time the shunt resistance is very large and the series resistance is very small hence they can be ignored for more simplified analysis.
The photovoltaic panel can be modeled mathematically and the voltage-current characteristic equation of a solar cell is given by the following equations.

Module photo-current, I_{ph}

$$I_{ph} = [I_{sc} + K_i(T - 298)] * \frac{I_r}{1000} \qquad \text{........ Equation 1}$$

Where: I_{ph} = photo-current (A), I_{sc}=short circuit current (A): a current obtained when array terminals are short circuited
K_i=short-circuit current temperature coefficient of cell at 25 °C and 1000 W/m^2; T=operating temperature (K), I_r=solar irradiation (W/m^2)

Module reverse saturation current, I_{rs}

$$I_{rs} = \frac{I_{sc}}{e^{(qV_{oc}/N_s kAT)} - 1} \qquad \text{........ Equation 2}$$

Where, q= electron charge = 1.6×10^{-19}C; V_{oc}: open circuit voltage (V); N_s= number of cells connected in series;
A=the ideality factor of the diode =1.6; k= Boltzmann's constant, = 1.3805×10^{-23} J/K

The module saturation current, I_0

It varies with the cell temperature, which is given by

$$I_o = I_{rs}(\frac{T}{T_r})^3[e^{\frac{qE_{go}}{Ak}(\frac{1}{T}-\frac{1}{T_r})}] \qquad \text{........ Equation 3}$$

Where: T_r = nominal temperature = 298K; E_{g0}= band gap energy of the semiconductor, = 1.1eV;

The current output of PV module, I_{pv} is given by:

$$I_{PV} = (N_P I_{Ph}) - [N_P I_o (e(\frac{q(V_{PV}+I_{PV}R_S)}{N_S AkTR_{sh}})) - 1] \qquad \text{........ Equation 4}$$

Where: N_p= number of PV modules connected in parallel (=1 for this case), N_s= number of PV modules connected in series (=36 for this case), R_s= series resistance (Ω), R_{sh} = shunt resistance (Ω), V_{PV} = V_{oc} = diode thermal voltage (V), this voltage is the Voltage obtained when array terminals are left open
Here for the simulation a 213.15W PV module is taken as the reference module for simulation and the name-plate details are given in the following table.

Table 1: Electrical characteristics data at 213.15W PV module

Rated Power	213.15W
Voltage at Maximum power (V_{mp})	29 V
Current at Maximum power (I_{mp})	7.35A
Open circuit voltage (V_{OC})	36.3V
Short circuit current (I_{SC})	7.84A
Total number of cells in series (N_s)	5
Total number of cells in parallel (N_p)	12
Modules in parallel	5
Modules in series	3

Furthermore the electrical specifications are under test conditions of irradiance of 1 kW/m^2, spectrum of 1.5 air mass and cell temperature of 25$^o{}_C$
Being illuminated with radiation of sunlight, PV cell converts part of the photovoltaic potential directly into electricity with both I-V and P-V output characteristics. Using the equations above (1-4), Simulink modeling is done in steps for each equation:
For Equation 1:

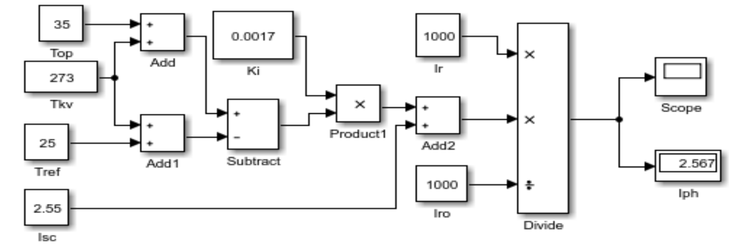

Figure 3: MATLAB Simulink model for equation 1

For Equation 2:

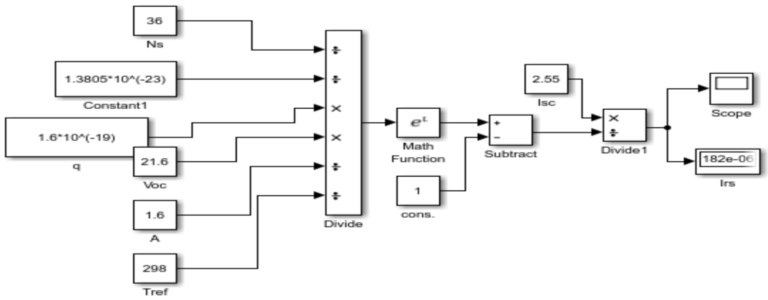

Figure 4: MATLAB Simulink model for equation 2

For Equation 3:

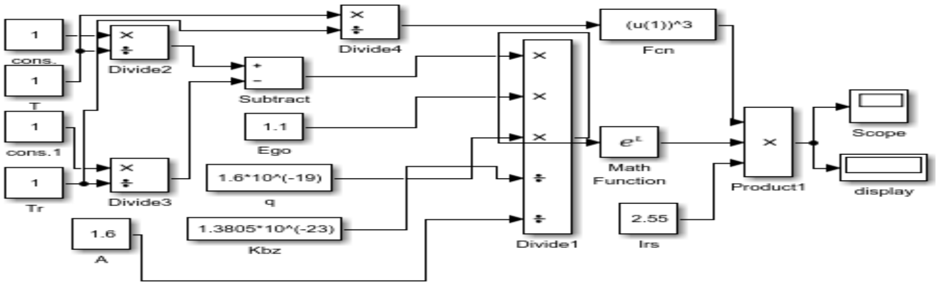

Figure 5: MATLAB Simulink model for equation 3

For Equation 4:

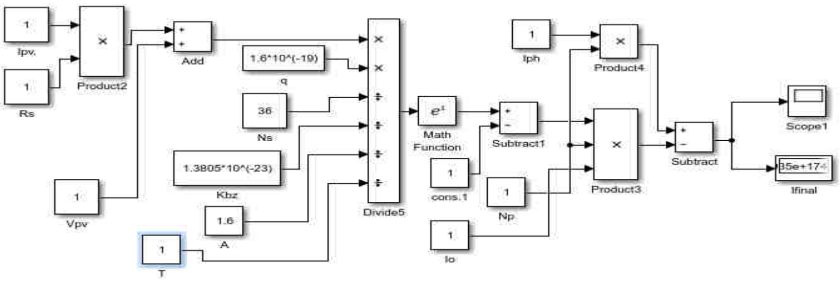

Figure 6: MATLAB Simulink model for equation 4

Now rearranging all the four Simulink models in to one and then runs the Simulink gives the following results. Notice that in order to make clear the modeling it is combined in to small subsystems in the aggregate system. Also external inputs such as the solar irradiation (W/m^2) and the operating temperature (^oC) are included. Finally the output will plot graph such as (Voltage verses Power) and (current verses voltage) at different samples of temperatures and solar irradiations.

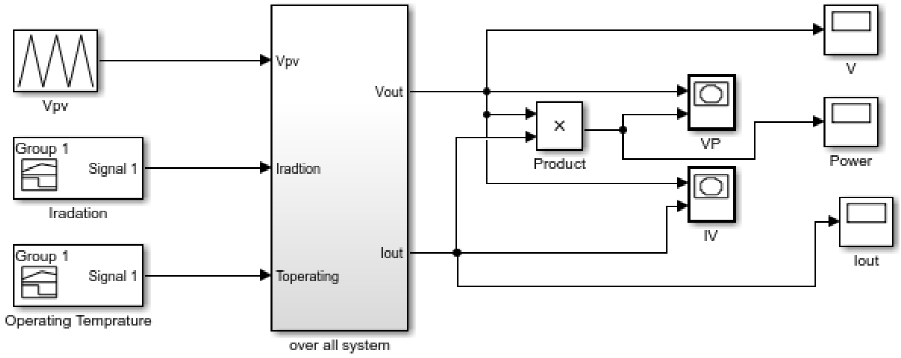

Figure 7: MATLAB Simulink, aggregate model for all equations including the sources

Simulink Graphs:

Before we go to the simulation results, first let's see the relationship between irradiation and temperature. Because these two terms have the major effect on the solar output powers. The correlation of temperature and irradiation is linear with correlation coefficient [4] value of 0.7473. This shows they have a strong linear relationship between solar radiation and surface temperature. The analysis of variance R^2 is 0.5585 that is, about 56 percent of the variability in temperature is accounted for by the straight line fit to solar radiation.

The Material used for the simulations is [Array type: 1Soltech 1STH-215-P; 3 series modules; 5 parallel strings]

A) At constant irradiation (1000W/m^2) and varying temperature(25^{o}C, 35^{o}C, 50^{o}C, 75^{o}C)

The following (figure 8) show current, power and voltage characteristic at constant irradiation and at different values of temperature. Hence as we can see from the graph power increases as temperature rises till some turning point and beyond this point power decrease as temperature rises and vice versa. Similarly the current has high value at high temperature until some turning point and beyond this point the current drops as temperature rises and vice versa. Both the current and power drastically decreases beyond the turning point regardless of the irradiation and temperature finally both drop to zero(when it drops to zero i.e. current and power are zero and voltage will be at its maximum which is V_{OC} this is when the array terminals are left open). The turning point is determined by the temperature value. For instance here the turning point voltage at 25^{0}C and 1000W/m^{2}is about 90V and at 50^{0}C and 1000W/m^2 is 80V. These turning points gives the maximum output power. The turning point is independent of the irradiation and it depends on the temperature value.

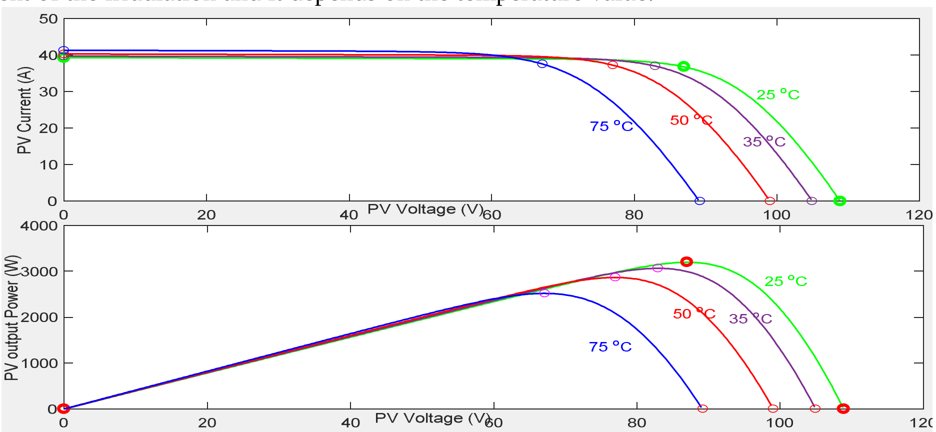

Figure 8: Current verses voltage and power verses voltage characteristics at constant Irradiation but varying temperature

B) At constant temperature (25^{o}C) and varying irradiations(0.2kW/m^{2,} 0.5kW/m^2, 1kW/m^2, 1.2kW/m^2)

The following graph (figure 9) the irradiation has direct relationship with both current and power. That is as the irradiation rises both current and power rises too. As we compare the temperature effect with the irradiation effect, the irradiation has higher influence on the output of the PV power. The current with some constant irradiation and temperature slightly decrease as voltage increase until some level, but beyond that level the current drastically decrease. For the case of the power as voltage increase the power increase considering content irradiation and temperature till some level of voltage but, beyond that level of voltage the power drastically decreases and finally goes to zero. The output power is maximum at the turning point and the turning point depends on the level of both temperature and irradiations. For instance the turning point at 25^{0}C and 1000W/m^2 is at about 90V and at 25^{0}C and 1200W/m^2 the turning point still at about 90V.

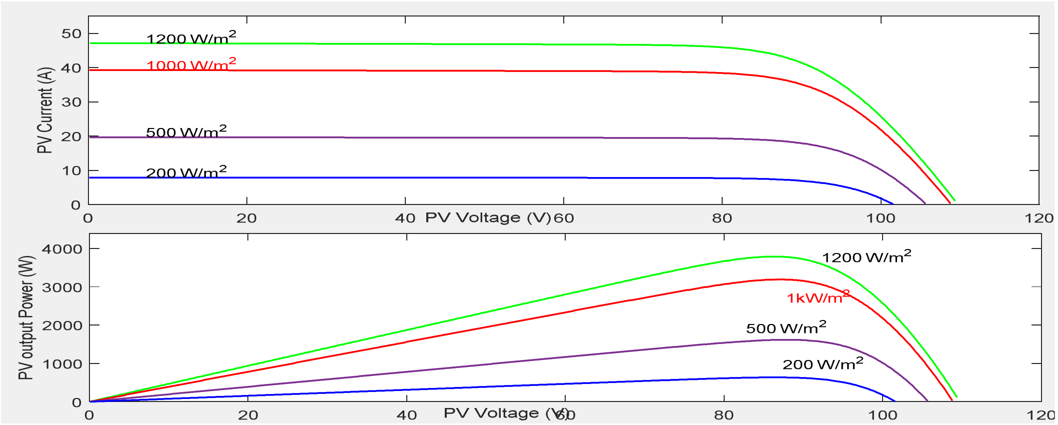

Figure 9: Current verses voltage and power verses voltage characteristics at constant temperature but varying irradiation

Hence the final conclusion here is that the turning point depends not on irradiations levels but on the temperature values. That is as temperature varies the turning point varies but it is constant though irradiations varies. Hence the temperature value has high effect on determining the maximum power output.

2.2 Wind Energy Modeling and Simulations[5]

Wind turbines convert the kinetic energy of the wind into mechanical power. Then the mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity to power homes, businesses, schools, and the likes. Hence in this thesis the case where the mechanical power is converted in to electrical power using a generator is be considered.

Cause of intermittency: Wind availability, Wind concentration, Wind Speed, Air temperature

Locations to choose for better power output for the wind power plant.

- Avoid slow wind location Avoid turbulent wind And it should never build on buildings

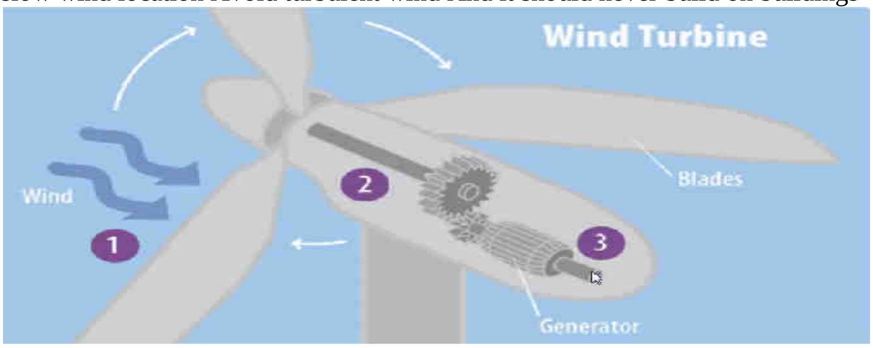

Figure 10: Wind turbines

Wind Modeling: The wind modeling should be able to simulate the time-based variations of the wind velocity, which consists of rapid wind speed changes and gusts (forcefully blowing wind). The wind velocity is given by the following formula.

$$V_w = V_{wB} + V_{wG} + V_{wR} \qquad \text{…….. Equation 5}$$

Where: V_w = Total wind velocity, V_{wB} = Base wind velocity (it is constant), V_{wG} = Gust wind component (it is represented as (1-cosine) terms) and V_{wR} = Ramp wind component (it is represented by ramp function). These winds are modeled using the s-function block of a MATLAB.

Wind Turbine Modeling: The kinetic energy is given as $KE = \frac{1}{2}mv^2$, where m is mass of the air, v is speed of the air. But the mass of the air is very small, we look at mass flow in a specific disc of area, A. Hence the mass flow of air through a disc is given as follows: $\frac{dm}{dt} = \rho Av$, where ρ is the air density. Then power generated by the turbine is given as:

$$P_W = \frac{1}{2}\frac{dm}{dt}xv^2 \;= \frac{1}{2}\rho A v_w^3 \qquad \text{…….. Equation 6}$$

However, the turbine captures only a fraction of this power. The power captured by the turbine (P_m) can be expressed as (Anderson and Bose 1983),

$$P_m = P_w C_P \qquad \text{…….. Equation 7}$$

Where C_p fraction is called the power coefficient. The power coefficient represents a fraction of the power in the wind captured by the turbine and has a theoretical maximum of 0.55 (David Richard et al 1993). The power coefficient can be expressed by a typical empirical formula as:

$$C_P = \frac{1}{2}(\gamma - 0.022\beta^2 - 5.6)e^{-0.17\gamma}$$ **…….. Equation 8**

Where β is the pitch angle of the blade in degrees and γ is the tip speed ratio of the turbine, defined as:

$$\gamma = \frac{v_w(mph)}{\omega_b(rad/s)}$$ **…….. Equation 9**

, ω_b= Turbine angular speed, v_w= total wind speed in miles per hour

Now equations (6-9) describe the power captured by the turbine and constitute the turbine model. Hence, the SIMULINK MATLAB implementation of the turbine model is given as follows

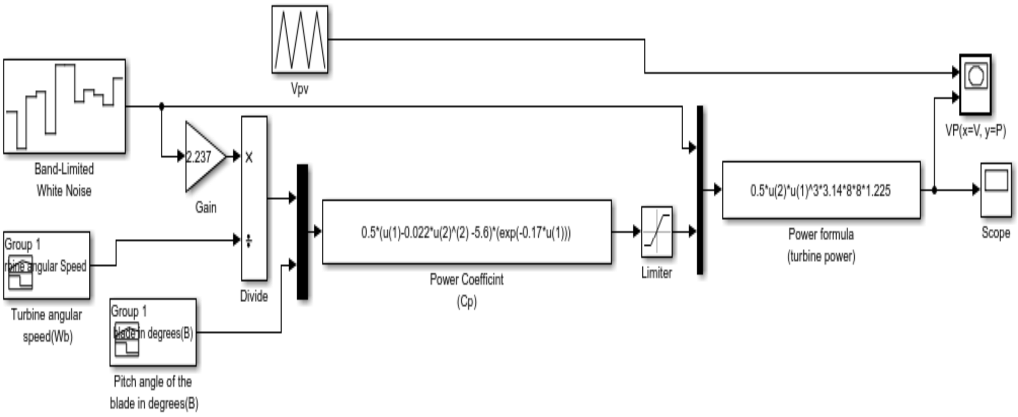

Figure 11: MATLAB Simulink model of wind turbine

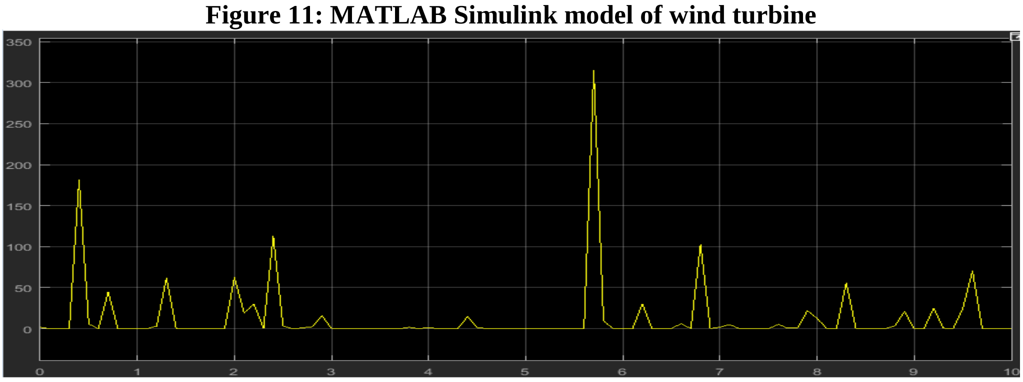

Figure 12: Typical wind output power

The output power is mainly depend on wind speed, it varies whenever the wind varies and by nature the speed of the wind varies even in short period of time (see figure 12 above). Now let's see the power verses wind speed graph characteristics in the following (figure 13 below).

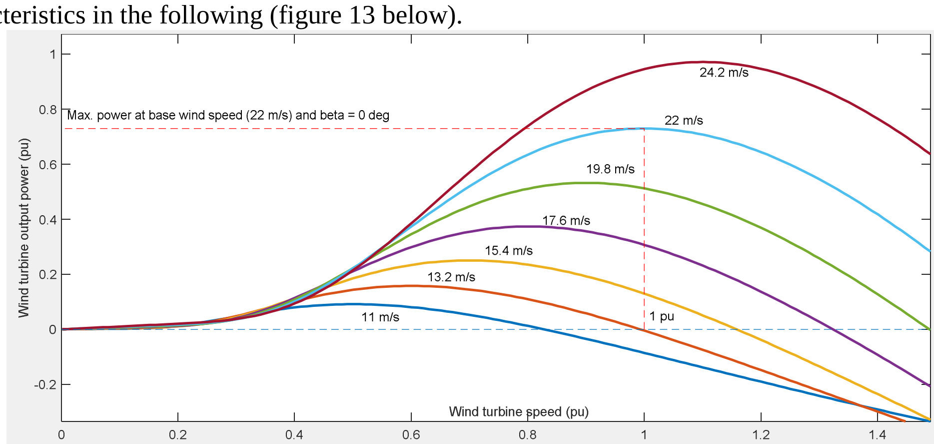

Figure 13: Turbine power characteristics verses turbine speed at different wind speeds (with bitch angle=0^0)

The relationship of power and wind speed is clearly given in the figure 13. The output power increases to the cubic of the wind speed until some optimum level. So that beyond that maximum level it falls. Hence, it will be more recommended to know the turning point to gather the maximum possible power.

Base Wind Speed: This speed is the base value of the wind speed which is used in the per unit system. It is also the average value of the expected wind speed of the environment under study. As many documents suggests the best wind speed for turning wind into the maximum amount of energy about 22m/s (50mph).

Pitch Angle of the Blade: The power generated by the wind turbine will vary depending on the angle at which the blades are positioned. Hence the effect of the angle is clearly seen when we compare both figures of (figure 13 & 14)

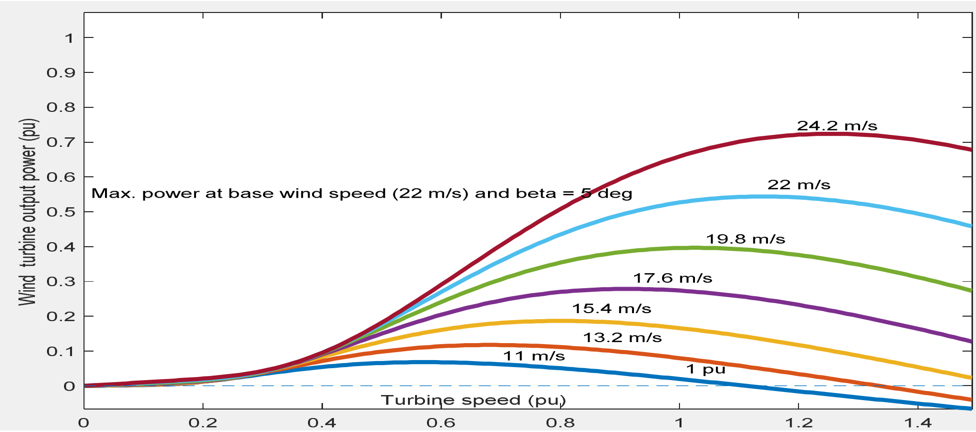

Figure 14: Turbine power characteristics verses turbine speed at different wind speeds (with bitch angle=5^0)

2.3 Micro Hydropower Modeling and Simulation[6]

Hydroelectric power production is a mature technology based on renewable energy. On a smaller scale, small hydroelectric power plants are widespread around the world. Small hydroelectric power plants have capacities ranging from 0.5 kW up to 10 MW. This range can be split into the four categories as follows: (1) Small hydro: have a capacity up to 10 MW, (2) mini-hydro: have a capacity up to 2 MW, (3) **micro-hydro:** have a capacity up to 0.5 MW, (4) Pico-hydro: have a capacity up to 5 kW.

Cause of Intermittency: Water current, Seasonal variations, Precipitation levels

The are two main types hydroelectric power production (refer figure 15 below)

i) Dam hydroelectric ii) Run of river hydroelectric.

The run of river hydroelectric is less expensive and have less power production capacity. Also it is subject to natural water variability hence it is more intermittent than the dam hydro so that this type of micro hydro is to be considered in the thesis.

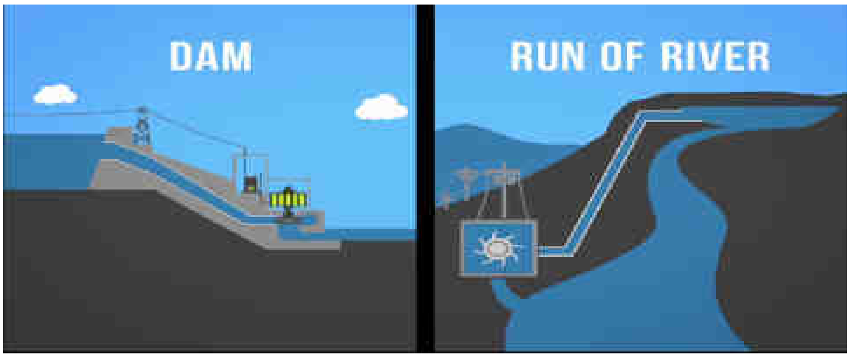

Figure 15: The two main types of hydroelectric power production: Dam and Run of river [6]

The power produced in the turbine varies with the flow rate, so the system operates or gains the steady state when the flow through the penstock gets constant.

Assumptions used in the modeling are:

- The velocity of water in penstock varies directly with gate opening

The mathematical equations related to the turbine power are given as follows:

$$Q = G\sqrt{H} \quad \text{........ Equation 10}$$

The developed power, P_m in turbine is given as

$$P_m = A_t H Q \quad \text{........ Equation 11}$$

Where: Q= flow rate (m^3/sec), G= gate opening in rad, H= height in meter, P_m=mechanical power, A_t=turbine gain given as: $A_t = \frac{1}{g_{fl-g_{nl}}}$, g_{fl}, g_{nl} are the full load and no load gate opening in pu (per unit), Equation 11 is modified to describe the motion of the water in penstock by the following equation

$$U = K_u G\sqrt{H} \qquad \text{…….. Equation 12}$$

Where, U is the velocity of the water in penstock and K_u is a proportional constant
The acceleration of the water fluid in the penstock is described by Equation

$$\frac{dU}{dt} = -\frac{a_g}{L}(H - H_o) \qquad \text{…….. Equation 13}$$

Where a_g =acceleration due gravity and L=length of penstock

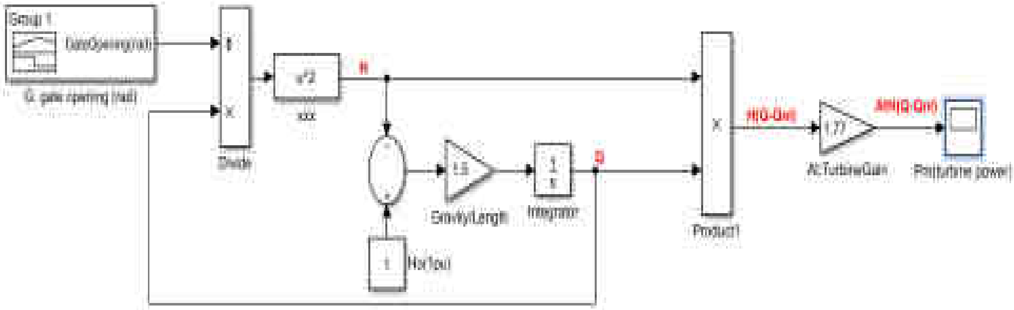

Figure 16: MATLAB/Simulink Model of micro hydro Turbine

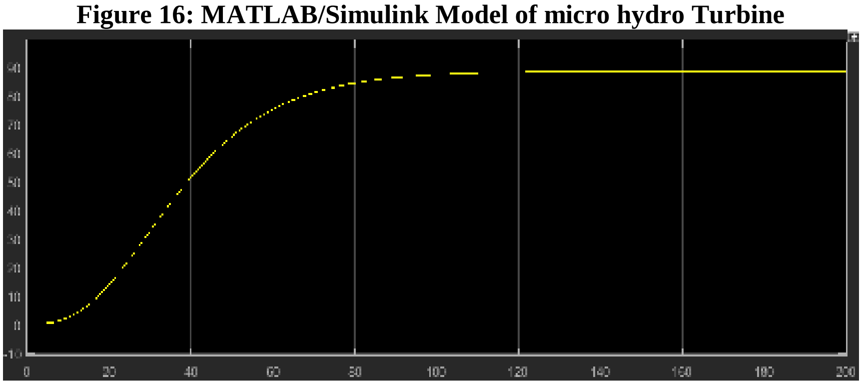

Figure 17: Output sample power of the micro hydro turbine

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